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RESEARCH MEMORANDUM

SIMULATION STUDY OF A HIGH-PERFORMANCE AIRCRAFT INCLUDING THE EFFECT ON PILOT CONTROL OF LARGE ACCELERATIONS DURING EXIT AND REENTRY FLIGHT

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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SIMULATION STUDY OF A HIGH-PERFORMANCE AIRCRAFT INCLUDING THE EFFECT ON PILOT CONTROL OF LARGE ACCELERATIONS DURING EXIT AND REENTRY FLIGHT*

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SUMMARY

A discussion is given of a simulation study of a high-performance aircraft conducted on the human centrifuge at the U. S. Naval Air Development Center, Johnsville, Pa. The centrifuge, in combination with an analog computer, provided a pilot-controlled simulator which subjected the pilot to linear accelerations similar to those he would encounter in exit and reentry flight.

Results of this study indicated that accelerations of the magnitude considered in this program did not significantly affect the pilot's ability to carry out his flight task when "flying" the airplane with auxiliary dampers operating. However, large oscillating acceleration patterns during reentry flight, such as might be encountered with certain damper failures, were found to make some reentries marginal and some impossible because of the effect on the pilot's ability to see and read instruments and satisfactorily control the airplane.

It is believed that the centrifuge simulator is a significant advance over static or "fixed-base" simulators for evaluation of pilot restraint, controls, instrument display, and pilot and airplane response.

INTRODUCTION

In the past, simulation studies of pilot control capabilities, including an analog-computer representation of the motion of the airplane, have been found to be valuable in the investigation of difficult piloting problems. For example, simulation studies have been made of

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*Title, Unclassifi [redacted]

roll coupling, pitch up, and pilot control during landing. In such studies, however, the pilots were not subjected to the sometimes violent motions that the airplane would encounter. At present, studies are being conducted of manned vehicles which will be required to exit from and reenter the earth's atmosphere and in which the pilot will be subjected to large accelerations during the exit and reentry phases. Due to the lack of actual flight experience under such conditions, it is desirable that the vehicle and its flight environment be simulated as closely as possible if the pilot and airplane responses are to be predicted with a certain degree of confidence. The subject of this paper is a discussion of a simulation study of a high-performance aircraft conducted on the human centrifuge at the U. S. Naval Air Development Center, Johnsville, Pa. In this study the pilot was subjected to the large linear accelerations that he would encounter in flight. This study was conducted as a joint effort between NACA and NADC and this opportunity is taken to acknowledge the excellent cooperation of the NADC personnel and particularly Dr. Carl Clark of the Aviation Medical Acceleration Laboratory for his efforts and supervision which contributed largely to the success of this program.

SYMBOLS

h	altitude, ft
M	Mach number
a_X	longitudinal acceleration, g units
a_Z	normal acceleration, g units

DESCRIPTION OF SIMULATOR SETUP

A portion of a trajectory, typical of that planned for the North American X-15 research airplane, was considered in this investigation and is shown in figure 1. In this figure, altitude h, Mach number M, longitudinal acceleration a_X, and normal acceleration a_Z are plotted against time which is given in seconds. This part of the trajectory starts at 48 seconds prior to engine burnout at an altitude of 60,000 feet, a Mach number of 2, on a zero lift or zero angle-of-attack flight path, and at a climb angle of 45°. During the powered phase of the exit, the thrust acceleration increases from 2g to about 4g. While under this acceleration and in the presence of out-of-trim moments in pitch and yaw due to misalinement of the thrust, the pilot's task is to fly with the wings level at zero angle of attack and sideslip. At burnout the acceleration rapidly approaches zero and disturbances are encountered due to the sudden termination of the misalinement moments. As the airplane reaches the higher altitudes, aerodynamic control becomes less effective and reaction control is used to keep the airplane at the proper attitude. If the pilot is able to perform his task properly during exit, the airplane will level out at about 250,000 feet. For reentry, the pilot pulls up to a prescribed angle of attack at about 200,000 feet, holds this angle of attack until the normal acceleration builds up to about 5g because of the increasing dynamic pressure, and then decreases the angle of attack in order to retain nearly constant acceleration until the rate of descent approaches zero. The angle of attack is then further reduced until level flight at 1g is obtained.

The main objectives of the centrifuge program were to answer the following questions:

Can the centrifuge under closed-loop control provide a useful dynamic simulation of a high-performance aircraft under large accelerations?

What are the effects on the pilot's ability to control the dynamic simulator when he is subjected to longitudinal accelerations of the order of 4g during exit and normal accelerations of the order of 5g during reentry?

What is the effect of various angles of attack and associated accelerations on the pilot's ability to fly the reentry?

How well can the pilot perform his task during reentry when subjected to large and rapidly oscillating acceleration patterns, such as might be encountered with certain damper failures?

The human centrifuge is located at the Aviation Medical Acceleration Laboratory at NADC. A photograph of this centrifuge is presented in figure 2. The centrifuge consists of an enclosed gondola mounted in a two-gimbal system on the end of a 50-foot rotating arm. The gimbal system consists of an outer gimbal which rotates about a horizontal axis perpendicular to the centrifuge arm and an inner gimbal which rotates about an axis in the plane of the outer gimbal and perpendicular to the axis of the outer gimbal. The total acceleration of the centrifuge gondola when the arm is set in motion is comprised of a radial component proportional to the square of the angular velocity of the arm, a tangential component proportional to the angular acceleration of the arm, and the vertical acceleration of gravity. The controlled gimbals allow positioning of the centrifuge gondola with respect to these accelerations so that the pilot is subjected to linear accelerations similar to those he would experience in flight. It should be noted that, since the centrifuge has only three degrees of freedom as compared with the six of the airplane, the accurate simulation of the linear accelerations must be done at the expense of angular motions which are not like those experienced in an airplane. However, it was found that under the large linear accelerations that were utilized in this study, the pilots were not significantly disoriented or distracted by these wrong angular motions or accelerations. The design capabilities of this centrifuge are a maximum radial acceleration of 40g with a maximum rate of 10g per second. A more detailed discussion of the centrifuge operation and capabilities is given in references 1 and 2.

Figure 3 shows a diagram of the closed-loop simulator that was used in this program. The simulator included an analog computer, a coordinate converter, and the centrifuge in which the subject pilot was placed. The closed-loop control was accomplished by feeding the three linear accelerations of the pilot, as determined by the analog computer from the equations of motions of the airplane, to a coordinate converter. Here the accelerations were converted to centrifuge commands in the form of gimbal angles and arm angular velocity and acceleration. The centrifuge then subjected the pilot to the three desired accelerations as indicated by the analog computer. While under these accelerations, the pilot observed the instrument panel, on which were displayed necessary quantities from the analog computer, and applied stick and rudder deflections which were fed back as input signals to the analog computer. Thus, the loop was completed, since the pilot's inputs actually controlled the motion of the centrifuge. The two main parts, that is, the analog computer and the centrifuge were located at a distance of approximately 3,500 feet apart and were tied together operationally by telephone lines.

The analog setup included a six-degree-of-freedom representation of the airplane motions, control equations (including auxiliary damper terms and pilot inputs), and computation of the dynamic pressure as a function of altitude and velocity. The aerodynamic characteristics were simulated as a function of both Mach number and angle of attack.

A simulated cockpit was mounted in the centrifuge gondola and included a right-hand console stick, rudder pedals, a left-hand ballistic or reaction control stick, and, for comparative purposes, a standard center control stick. An instrument display panel, which is shown in figure 4, was provided for the pilot. The primary instruments used in this program included an attitude ball indicating roll and pitch angles, and indicators presenting angle of sideslip, angle of attack, normal acceleration, inertial altitude, inertial velocity, inertial rate of climb, roll rate, and heading. Positioned below the panel were damper-malfunction indicator lights and associated switches.

The pilot was secured in the gondola by an integrated harness arrangement. For head restraint the subject's helmet was fastened inside a bucket-type headrest by a steel cable which was attached to the helmet and fixed to the back of the headrest.

RESULTS AND DISCUSSION

The remaining part of this paper discusses some of the more pertinent findings of this study. Included in these results are some of the pilots' comments and their evaluation of the dynamic simulator. A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract and index page.

A typical run on the centrifuge was started by manually bringing the centrifuge up to the initial condition of 2g thrust acceleration. From this initial condition, the pilot would actually start his flight and assume control by turning on the engine switch on the instrument panel. This switch started the integrators of the analog. The angular velocity of the centrifuge would then increase, and the pilot was subjected to the increasing thrust acceleration. During this period of prolonged acceleration, the pilots experienced a drainage of the sinus and a feeling of fullness in the throat which resulted in frequent coughing. Breathing during this time was difficult, usually rapid and shallow. At burnout, oscillations started because of the sudden removal of the thrust misalinement; these oscillations could be stopped by the use of aerodynamic control if the pilot reacted promptly. If the pilot reacted slowly, the oscillations persisted to higher altitudes and the use of reaction control was found necessary. At burnout, the centrifuge, unable to simulate less than 1g, would come to rest. The pilot would then fly the 0g portion of the trajectory (about 2 minutes duration) statically (with the centrifuge at rest) at 1g. As the airplane reentered the atmosphere, the centrifuge would again rotate in response to the buildup of normal acceleration. The reentry required rapid scanning of a relatively large number of instruments and a high degree of concentration. The high rate of scanning found necessary in this study indicated that the relocation and possibly combining of certain instruments for a more nearly optimum display should be considered. With all dampers operating, three reentry conditions were considered. These were an angle of attack of 15° with an acceleration of 5g until recovery, 20° with 4.5g, and 25° with 4g. Little difference was noted in these reentry conditions except that the 25° case required slightly more control than the 20° or 15° reentries. The difference between 4g and 5g normal acceleration had no noticeable effect on the pilot's ability to reenter. Only moderate "greyout" was experienced during the reentries. Safety stops were included in the simulator which would automatically terminate the run if the commanded acceleration exceeded 8g; however, the subjects rarely received an acceleration over 6g.

It is of interest to note here, before discussing some of the damper failure results, a few comments concerning the comparison of the center control stick with the right-hand stick. The majority of the flights were made with the right-hand stick. However, for the few flights with the center stick, the pilots felt that it was a good controller at low accelerations. Above about 2g, however, two hands were used and the center control stick was considerably more difficult to use than the right-hand stick because of the acceleration effects on the hand and arm positions.

An important part of the investigation was to determine the ability of the pilot to control the airplane during reentry under certain damper failures. Figure 5 shows the effect on reentry of one of the damper failure conditions investigated. Shown are the lateral accelerations during a 25° angle-of-attack reentry (starting 190 seconds after the beginning of the flight) for the case of all dampers operating and the case of a yaw-damper failure. It should be mentioned that in the present investigation the damper system consisted of dampers about all three axes and, in addition, a crossfeed of yaw rate to the roll control surface. In the reentry shown in figure 5, the crossfeed and yaw damper were both not operating. This condition would correspond to a failure of the yaw-rate sensing gyro. With all dampers operating, the pilot was able to maintain practically zero lateral acceleration during reentry. However, with the damper failure a maximum lateral acceleration of about ±2g was encountered. Even though the pilot was able to fly the airplane to recovery under this failure, he experienced some difficulty in reading the instruments during the motion and considered the system used for body and head restraint necessary in avoiding loss of orientation and minimizing distractions from being jostled about.

Another type of damper failure that was simulated is shown in figure 6. Shown in this figure is the normal acceleration during reentry with all dampers operating and with the pitch damper failed. At about 225 seconds, the pilot was unable to cope with the high oscillating accelerations, and the run was automatically terminated when the safety stop was reached at 8g. It is of interest to note the change in frequency of the oscillation as the airplane reenters the atmosphere. It should be mentioned that in the static or "fixed-base" simulation tests, where the pilot was not subjected to normal accelerations, he was able to reenter under this condition of pitch-damper failure about 60 percent of the time. However, the pilots never did reenter successfully in the dynamic tests on the centrifuge. The pilots believed that the oscillating acceleration was such that it did not permit them to control as precisely as required.

Although no specific results will be discussed for reentries with roll-damper failure, reentries with this failure were found to be extremely difficult. For a small percentage of the cases, recoveries were made with very precise control of a low-angle-of-attack reentry.

CONCLUDING REMARKS

The centrifuge simulator was found to be a useful dynamic simulation of a high-performance aircraft under large accelerations. It is believed that this simulator is a significant advance over fixed-base simulators for evaluation of pilot restraint, controls, instrument display, and pilot and airplane response.

For the trajectory considered in this study, and with all the dampers operating, the pilots were generally able to carry out successfully their flight task while under longitudinal acceleration of the order of 4g and normal acceleration of the order of 5g, even though some physiological effects were noted. However, large oscillating acceleration patterns, such as might be encountered in the case of certain damper failures, were found to make some reentries marginal and some impossible because of the effect on the pilot's ability to see and read instruments and satisfactorily control the airplane.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 18, 1958.

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1. Crosbie, Richard J.: Utilization of a System of Gimbals on the Human Centrifuge for the Control of Direction of Acceleration With Respect to the Subject. Rep. No. 4, Project NM 001 100 303, Aviation Medical Acceleration Lab., U. S. Naval Air Dev. Center (Johnsville, Pa.), Aug. 2, 1956.

2. Clark, Carl, and Crosbie, Richard: Centrifuge Simulation of Flight Accelerations. Project TED ADC AE-1410 (NM 11 02 12.6), Aviation Medical Acceleration Lab., U. S. Naval Air Dev. Center (Johnsville, Pa.), Sept. 17, 1957.

SAMPLE TRAJECTORY

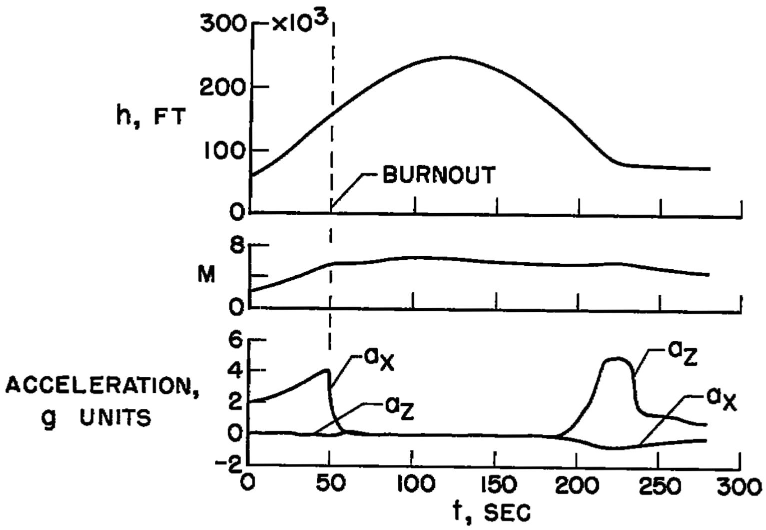

Figure 1

HUMAN CENTRIFUGE

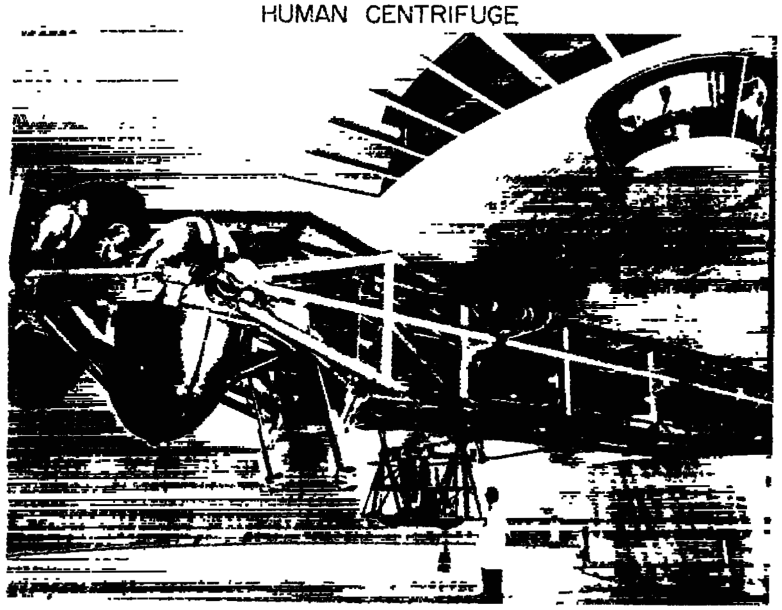

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Figure 2

DIAGRAM OF CLOSED-LOOP
ANALOG-CENTRIFUGE-PILOT SIMULATOR

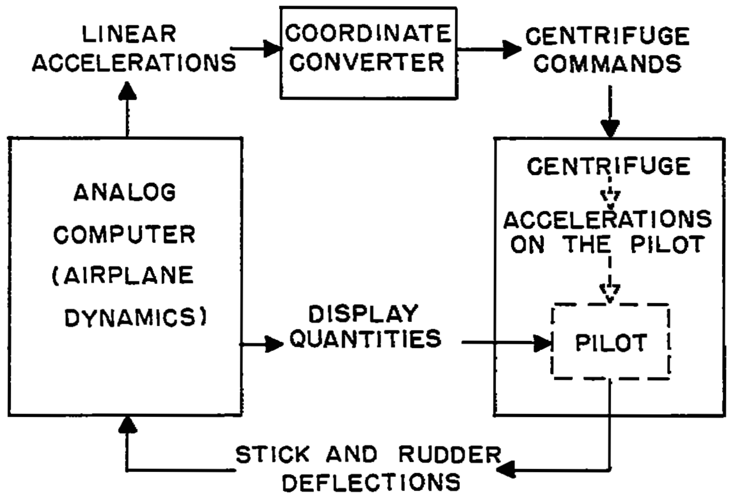

Figure 3

INSTRUMENT-DISPLAY PANEL

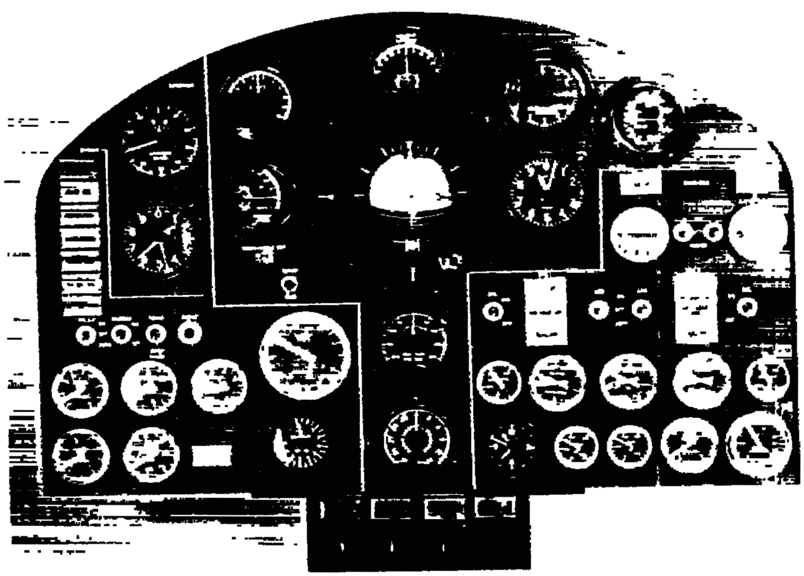

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Figure 4

EFFECT OF YAW-DAMPER FAILURE

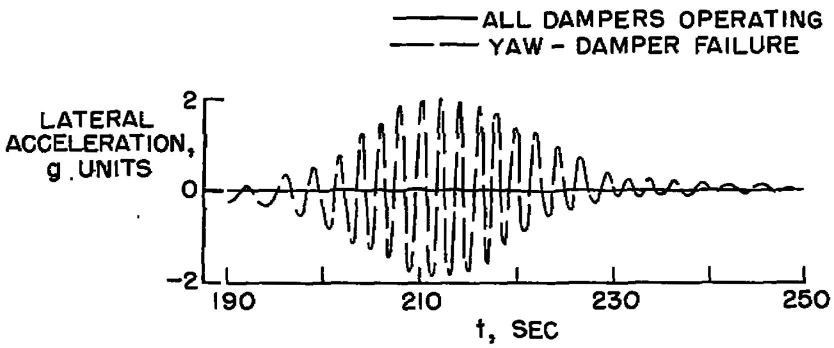

Figure 5

EFFECT OF PITCH-DAMPER FAILURE

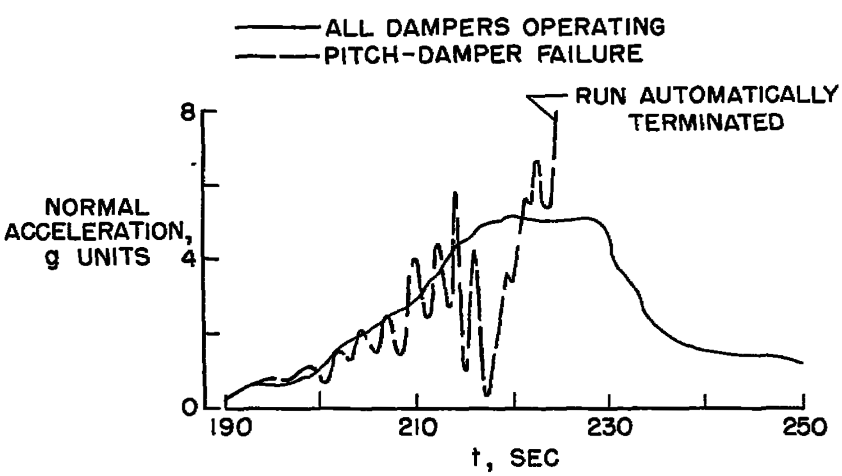

Figure 6

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